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EVALUATION OF HUMAN EXPOSURE TO LOW FREQUENCY FIELDS

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SUMMARY

The biophysical model concept described in this paper might be suited as a basis of discussion to determine and define limits of exposure to electric or magnetic fields below 100 kHz, including 50/60 Hz.

The electric field strength within the tissue in the environment of excitable neurons and muscle cells is considered decisive for the biological effect. Threshold values of field strength or current density inducing biological effects are compiled from experimental and theoretical studies. On the basis of these data it is possible to establish "safe," "dangerous," and "hazardous" current density curves as a function of frequency. The criterion for the definition of injury is the elicitation of ventricular fibrillation which must be avoided. To define exposure limits, the field strength or current density causing injury should be reduced by a factor of 300. The arguments supporting this wide safety margin are discussed.

In the second part of this paper the electric and magnetic field strength in the human environment is correlated with the corresponding electric current density induced in the human body. This enables "safe," "dangerous," and "hazardous" levels of current density in the human body to be correlated with the external electric or magnetic field intensity. Parts of the concept presented in this paper have been adopted in the DIN/VDE Regulation No. 0848 which defines the limits for frequencies above 10 kHz.

1.0 INTRODUCTION

In the past few years more and more persons have been exposed to strong fields with frequencies below 100 kHz in areas other than power engineering application (16.6, 50, 60 Hz). Magnetic fields have been of special interest due to their penetration characteristics for the human body. Various types of induction heating systems in the low and medium frequency range are examples of sources of strong magnetic fields. Biologic effects occur with a sufficient intensity of the fields; examples include hair movement on the body in strong electric fields or the generation of light and flickering phenomena, and subjective complaints such as headache in strong magnetic fields. In medicine, the effects of strong magnetic fields are being used in imaging processes (nuclear spin tomography) or for therapeutic purposes (magnetic field treatment).

The reason for the uncertainty in determining personnel health limits for frequencies below 100 kHz is that so far a sufficiently secured model idea has not become known for estimating the risk in the frequency range involved here. Such a concept, however, is necessary as one cannot explain that the full frequency range can be studied by experiments with good results similar to those obtained in the sphere of power engineering fields. This paper describes a simple concept that may serve as a basis in the discussion on the definition of personnel health limits. Parts of these ideas and considerations have already been adopted in the VDE regulation (1984) defining limits for frequencies above 10 kHz.

2.0 BASIS OF THE CONCEPT FOR EVALUATING HUMAN EXPOSURE

When possible health risks from the influence of electric and magnetic fields on man are evaluated, primarily those biologic effects are considered which originate from a direct action on the cells in nerve and muscle tissues. The physical quantity determining the biological effect is the electric field strength in the tissue surrounding the living cell. This can be inferred from both theoretical considerations where the depolarization of the cell membrane potential is directly related to the magnitude of the electric field intensity in the cell environment, and from the experiments confirming this concept (Bernhardt, 1983). A great volume of experimental data on stimulus thresholds for different nerves and muscle cells, however, has often been expressed in the form of electric current values and not as field strength values. Only comparatively few papers disclose data on the field strength thresholds. Here, the electric current density will be used as the decisive parameter in assessing the biologic effects at cell level. As far as necessary, the values given for the specific conductivity can be used to convert the current density in the tissues into field strength.

Selection of the current density as a measure of action on the cellular level also offers the possibility to extrapolate conditions in the human body from studies of animal experiments or from measurements taken at isolated cells, by way of mutual comparison of the current densities. It is irrelevant whether the electric current density surrounding a cell is introduced into the body through electrodes or induced in the body by external electric or magnetic fields; however, the current paths within the body may be different.

In the evaluation of human exposure to electric and magnetic fields below 100 kHz, the following steps are relevant:

a) Experimental data on the thresholds for stimulation of excitable cells are combined in a current density/frequency diagram. A current density "envelope" is used as the "threshold curve of possible acute health hazard"; another current density curve is plotted as the "injury threshold."

b) Some experimental values in relation to phenomena depending on current densities below the stimulus thresholds, in combination with theoretical considerations, define a current density curve below which a direct influence on neurons can no longer be expected ("limit of the safe range").

c) The current density curve between the "safe" and the "dangerous" current density curves may serve as the limit value curve in evaluating exposure to external electric and magnetic fields.

d) Electric and magnetic field intensities in man's environment are related to the electric current densities they induce within the human body. This allows correlation of the internal current density curves with the external field strengths, and definition of "safe" and "dangerous" field strengths.

e) It must be verified that no direct or indirect biological effects are caused by other mechanisms which could also be a hazard to man at lower field strengths than those defined in d).

3.0 DEFINITION OF "SAFE" AND "DANGEROUS" CURRENT DENSITIES

In this section I consider threshold values of the electric current density for different biological effects in nerve and muscle tissue. The values are summarized in the current density/frequency diagram of Figure 1. A more profound treatment is given by Bernhardt (1983).

3.1 Stimulation Thresholds

3.1.1 Stimulation of Sensory Receptors

Curves a_1 and a_2 in Figure 1 give threshold values for the stimulation of sensory receptors taking place immediately underneath the surface electrodes (Geddes et al., 1969).

3.1.2. Disturbance of Cardiac Stimulation

When electric field intensities in the environment of myocardial cells are sufficiently high, the process of intracordial stimulation can be influenced. Two processes are relevant here: extrasystoles, and atrial and ventricular fibrillation. While premature heart contractions in the course of the regular pulse sequence are deemed disturbances of the cardiac stimulation, ventricular fibrillation is the most frequent acute cause of death in the electrical accident. Even though there are numerous studies on current intensity, duration of exposition, and current path in electrical accidents, information on the field strength or current density values leading to disturbance in cardiac stimulation can hardly be found.

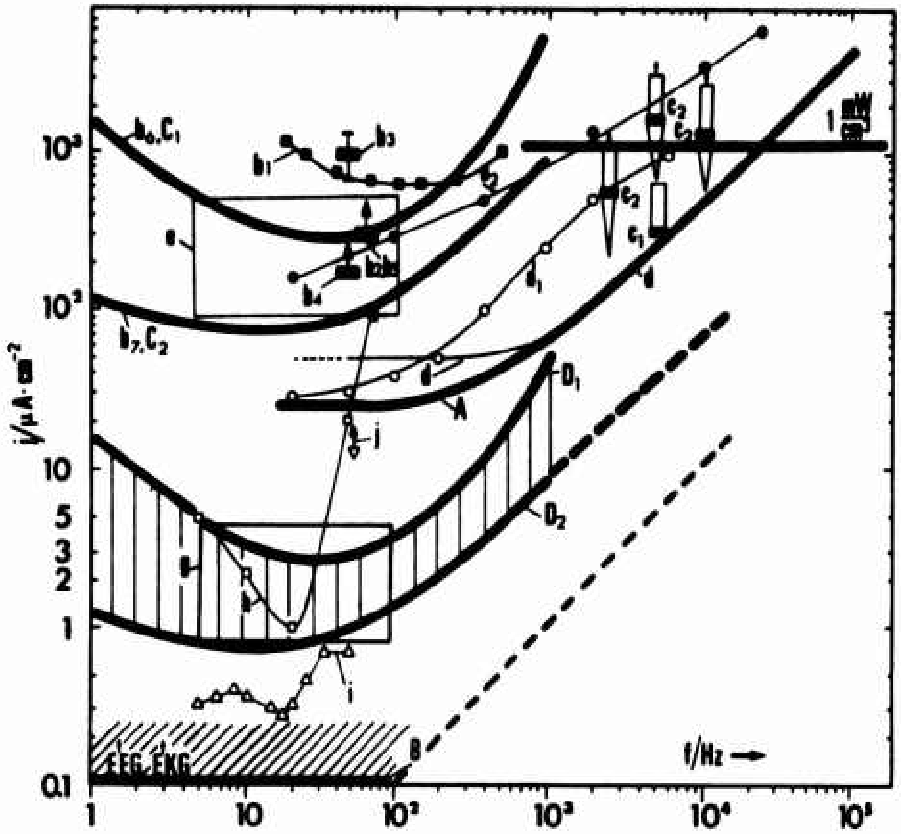

Figure 1. Threshold values of the electric current density for different biological effects. Explanations are given in the text.

In view of the "worst case" event, the risk of ventricular fibrillation increases with the duration of the current flow. With a current flow duration of a single period, more than 100 mA are necessary to elicit fibrillation; whereas with a duration of 100 periods, the fibrillation threshold ranges about 0.7 mA (Roy et al., 1977). Therefore further statements will be based on exposition times of 1 second or longer. Thresholds for fibrillation elicitation are higher than the stimulation thresholds for extrasystole elicitation, by the factor of 3 to 5 (Antoni, 1982, Weirich et al., 1982).

The biophysical basic mechanisms involved in creation and further course of ventricular fibrillation in studied animal hearts are the same as the mechanisms to be found in the hearts of bigger animals, so information on the electric field strengths for the current densities in the tissue allow results obtained in animal experiments to be interpreted to the human body. The following thresholds of current densities for ventricular fibrillation have been found:

- Irnich et al. (1974) measured the stimulation and fibrillation thresholds with dogs and recorded these values as a function of the frequency (16-300 Hz , b_1 in Figure 1).

- Roy et al. (1976), using cardiac catheters, found the threshold values to be above 300 μA/cm^2 (b_2 in Figure 1) - depending on the catheter size.

- Jacobsen et al. (1974) measured the field intensity at pig hearts and quoted a confidence range for the electric field strength threshold to elicit ventricular fibrillation between 224 and 429 mV/cm (mean value 327 mV/cm). The current density values converted for a myocardial conductivity of 0.25 S/m are plotted under b_3 in Figure 1.

- Osypka (1963) quoted a threshold value of 8 V/m as sufficient to start the stimulation process at the heart. Calculation and conversion lead to a current density of 2.0 A/m^2 (200 μA/cm^2, b_4 in Figure 1).

- Studies with the human heart by Watson et al. (1973), using 1.8-cm^2 electrodes, resulted in a threshold of 300 μA/cm^2 to elicit ventricular fibrillation (b_5 in Figure 1).

- The current values quoted by Weirich et al. (1982) for the stimulation threshold and the fibrillation threshold with 1 second of stimulation are plotted in Figure 1 as current density curves in a manner that the curves roughly correspond to the data obtained by other authors (Curve C1: fibrillation threshold; curve C2: diastolic stimulation threshold). As a result of this procedure, the uncertainty in relation to the shape of these curves --related to the human body --is a factor of 2 or even more.

3.1.3 Stimulation of Isolated Cells

Using microelectrodes, several authors measured the thresholds of the current for extracellular stimulation of isolated neurons, with varying spacing of the microelectrode from the cells. Current density values for the stimulation thresholds can be calculated from these current intensity/spacing measurements.

There is a great variability between the individual studies, possibly due to different spacings from the next node of Ranvier. Some of these measurements have been interpreted (Ranck, 1975, c_1 and c_2 in Figure 1).

The extracellular stimulation experiments with isolated cells confirmed the theoretical concepts (Bernhardt, 1973) that substantially smaller current densities are required for stimulation of an excitable cell with parallel orientation of the electric field strength than with normal orientation.

3.1.4 AC Stimulation Threshold

Schaefer (1940) quoted a formula to express the stimulation threshold for nerve/muscle systems as a function of frequency. The formula gives the stimulation threshold of alternating current in the form of a threshold ratio to the 50-Hz threshold for different frequencies. There is a linear threshold increase with a frequency increase in the high frequency range. Here reference is made to current density values. When a 50-Hz threshold of 0.5 A/m^2 is selected, the current density ranges for isolated-cell stimulation, designated by (c) in Figure 1, are just above that curve (curve d in Fig. 1).

3.1.5 Induction of Membrane Potentials by Electric Fields Surrounding a Cell

A threshold value for stimulating effects of roughly 300 μAcm^2 must be expected for theoretical reasons too. As a result of charge transfers inside and outside the cells, alternating electric fields induce a membrane potential

in biological cells, which is determined not only by the strength and frequency of the field but also by the size and shape of the cell and its orientation in relation to the electric field (Bernhardt, 1973). The field-induced potential difference was measured by using intracellular microelectrodes (Bernhardt, 1983). The measured values confirmed the theoretical value. From the theoretical relationship the field strength in the cell environment can be calculated for a variation of the membrane potential by 10 mV, which may result in a stimulation effect in excitable cells. The magnitude of the corresponding current density range is identified by range e in Figure 1.

3.2 Hazardous Current Density Curves

As conclusion of chapter 3.1, curve A in Figure 1 can be considered the "envelope" which delimits the experimentally found current density values for stimulating effects. Current densities produced by electrodes or induced by external electric or magnetic fields may result in a stimulation effect on neurons and muscle cells with values above the plotted curve A. An unexpected stimulation of muscle cells may lead, for instance, to a situation of fright that can trigger a hazard. When, after a considerably long duration of influence by current densities above the "envelope," cerebral nerves in major spheres are stimulated at the same time, acute neurologic symptoms cannot be excluded (e.g., increased blood pressure, convulsions in vessels, spasms of the breathing system, paralyses). In this sense, Curve A may be called the "threshold curve for a possible hazard."

The higher density curve C_1 is used here as the "threshold curve of injury." Ventricular fibrillation in the sense of a definition of the injury is considered here to be that event which must be avoided. A sufficiently wide safety margin must be selected when personnel health limits are defined.

With higher frequencies, the threshold values for stimulating effects are close to current densities that result in a thermal effect. A current density of roughly 1 mA/cm^2 generates a specific absorption rate of 2 $mW \cdot cm^{-3}$ in the tissue (specific conductivity of 0.2 $S \cdot m^{-1}$), which may result in a rise in temperature by 1 °C in muscle tissue over a period of 1 hour (without consideration of thermal transfer by thermal conduction and blood circulation). With a current density of 5 mA/cm^2 (reached with curve A at 100 kHz), the same heating effect occurs in less than a few minutes. The comparison shows that an injury possibly occurs as a result of a stimulating effect rather than a thermal effect for a short period of time, with frequencies up to the range from 30 to 100 kHz.

3.3 Biological Effects with Current Densities Below the Stimulation Thresholds

Electrophysiologic studies have shown that information can be transferred between neuronal elements even without action potentials (Schmitt, 1976). Minor potential variations of 0.1 mV in one neuron may influence the activity in other neurons by a synaptic effect. Today the view prevails that in the brain small graded potential variations in the range of 0.1 mV are important in many processes. It must be expected, therefore, that current densities in electrical events in the brain, which are below the stimulation thresholds, may influence functions of the brain. As experimental studies in this direction could so far hardly be carried out, an attempt should be made to delimit the range in question on the basis of a small quantity of data only.

3.3.1 Electro- and Magnetophosphenes

The generation of light effects (phosphenes) under the influence of electric currents or magnetic fields has been known for a long time. Lövsund et al. (1980, 1981) localized the mechanism to certain areas on the retina.

Adrian (1977) measured the threshold current intensities for phosphene generation with alternating currents of different frequencies. As one electrode was applied directly at the eye of the test subject, Adrian was able to give the minimum current density for the generation of phosphenes. Adrian's data is plotted in the form of curve h in Figure 1.

Silny (1981) studied the subjective perception of flicker phenomena in volunteers exposed to strong low-frequency magnetic fields. With a homogeneous magnetic field being generated by a Helmholtz coil arrangement, the electric current density in the peripheral spheres of the heat (eye, cerebral cortex) can be estimated (curve i in Figure 1). The magnetic current densities determined here are below the threshold density of 3 $\mu A/cm^2$ quoted in literature for biologic effects, but this may be due to the method of calculation.

3.3.2 Variation of Reaction Potentials in Low-Frequency Magnetic Fields

Silny (1981) examined test persons to study the influence of 50-Hz magnetic fields on optically generated reaction potentials. A 50-Hz magnetic field with an induction of 60 mT changes the polarity of the observed reaction potential, corresponding to a magnetically induced current density of roughly 14 $\mu A/cm^2$ in the cerebral cortex (j in Figure 1).

3.3.3 Field-Induced Potential Differences of 0.1 mV

The idea outlined in section 3.1.5 is adopted here with a shift downward by the factor 100 of the range e of Figure 1 between 1 and 100 Hz (now 0.1 mV instead of 10 mV potential difference). The current density range g in Figure 1 must be assigned to field-induced potential differences in the range of 0.1 mV within this frequency range.

If potential-difference variations of this magnitude should be the cause of certain biologic effects that have been noted, the corresponding thresholds for the current density ought to come under the magnitude of 1-3 $\mu A/cm^2$. The relevance of field-induced potential differences of 0.1 mV, however, needs further and more specific explanation by continued studies and experiments.

3.4 Safe Current Density Curve

One may estimate "safe" field-induced current densities by considering the naturally flowing currents in the brain as a result of the electrical events in the brain. The measured values, which are recorded using extracellular electrodes on the cortex surface (typical values 50-100 μV with 1-cm electrode spacing), furnish a current density of roughly 0.1 $\mu A/cm^2$. The current densities within the brain may vary strongly at a microscopic level--depending on the cerebral nerve anatomy--and may well be as high as 10 to 100 $\mu A/cm^2$, e.g., on the surface of cells that are electrically active at the time of measurement. The comparison against the naturally flowing currents, in combination with the frequency range from 1 to 100 Hz, leads to the

conclusion that brain current densities due to external electric or magnetic fields or generated through electrodes should have no influence on neurons when the current densities remain below 0.1 $\mu A/cm^2$ approximately.

This limit is indicated by curve B in Figure 1. This curve may be considered to be a "curve of the limits of the safe range." Biologic effects as the consequence of direct action of electric fields onto neurons must be expected above this curve, and their existence has been demonstrated in the range between 5 and 100 Hz.

3.5 Limit Value Curve

Curve D_2 in Figure 1 is suggested as the limit value curve in evaluating human exposure to external electric and magnetic fields. The safety margin from curve C_2 is 100. Additional theoretical and empirical studies will have to demonstrate whether this safety factor is open to reduction or whether the factor must be increased.

A particular importance must be awarded to the brain as the most important switching and control center of the body. Today the view prevails that small potential variations below the depolarization processes required for action potentials have a role in many cerebral functions which is greater than has been assumed so far.

Some experimental results have shown (cf. section 3.3) that, in the low frequency range, effects occur with current densities below the stimulation current densities by a factor up to 100. Further information is urgently needed in this respect, mainly to demonstrate whether the health condition will be impaired by long-term exposure to current densities in this range. Here, too, the field intensity or current density in the brain should be known so that the results gathered in animal experiments can be transferred to the human body. The comparatively wide safety margin takes the following points into consideration:

- There is an uncertainty in relation to the current density values that are required for elicitation of extrasystoles and ventricular fibrillation.

- The majority of the threshold value data originates from animal experiments. The translation of this data to conditions in the human body needs more detailed definition.

- Regarding the stimulation thresholds, the varying individual sensitivity as well as the increased sensitivity in persons with manifest disturbance in stimulation of the heart must be taken into account.

- Because of insufficient long-term experience, safety factors are required. The subjective complaints reported so far after exposition for an extended period of time (such as headache) result in current density values below the fibrillation thresholds by a factor between 10 and 100. Such current densities should not be exceeded in relation to the brain.

- With the selected safety factor, moreover, current densities such as those occurring in the low frequency range during therapeutic magnetic field treatment will be precluded.

- As human exposition to electric or magnetic fields is discussed, there is a substantially higher uncertainty with the precise paths of the field-induced currents than with galvanic current supply into the human body.

- The data on conversion of external electric and magnetic fields into current density in the body involve different assumptions and premises that must be balanced with the safety factor.

4.0 BODY CURRENT DENSITIES INDUCED BY EXTERNAL LOW-FREQUENCY FIELDS

This section quotes the external electric field strengths (E_a) and magnetic field strengths (induction B_a) which, as a function of frequency, induce certain mean electric current densities in the human body. On the one hand, the current densities for the heart and its environment are analysed; on the other hand, the human head, with the brain as the most important switching and control center of the body, will be dealt with as another "critical" organ. Curves A, B, C_2, and D_2 of Figure 1 are translated into field intensity/frequency diagrams, employing the following findings and data:

Studies on distribution of the electric field in homogeneous spheres (radius R) exposed to a plane electromagnetic wave, show that with frequencies below approximately 30 MHz and in biologic material (characterized by ϵ and σ), the electric field strength in the sphere is composed of an electric term E_i^E and a magnetic term E_i^B (Lin et al., 1973; Bernhardt, 1979):

$$E_i^E = \frac{3\epsilon_0 \cdot \omega}{\sigma} \cdot E_a = \bar{A}_k \cdot \frac{f}{\sigma} \cdot E_a \qquad (1)$$

wherein $A_k = 6\pi\epsilon_0$ and

$$E_i^B = \pi \cdot f \cdot R \cdot B_a \quad \text{(for sinusoidal fields)} \qquad (2)$$

Corresponding studies with ellipsoids (Johnson et al., 1975; Durney et al., 1975) have shown that there, too, in a rough approximation, the external electric and magnetic fields may be considered separately and independently of each other.

Elongate spheroids with longitudinal axes parallel to the external E vector must be deemed the "worst case" with external electric fields. For this reason, the electrically induced field intensities in the body can be determined from information on the total of the absorbed power P for which values are at hand.

Further information from studies on the distribution of the electric field or the absorbed power in different parts of the human body have shown that with frequencies below 10 MHz, the internal field intensity increases directly proportionally to frequency with a predetermined external electric field strength (Gandhi et al., 1979). This means that the application of a suitable value for $\bar{A}$ is possible in the relationship between the internal and the external field intensity Gl (1).

Regarding magnetically induced current densities, the cardiac region and the brain are each considered as homogeneous spheres. The resulting current densities are as follows:

$$j^E = \bar{A} \cdot f \cdot E_a \tag{3}$$

$$j^B = \Pi \cdot R \cdot \sigma \cdot f \cdot B_a \tag{4}$$

(The current densities must be added vectorially when both an electric and a magnetic field are present.)

With suitable values for $\bar{A}$ and σ, electric current densities for the head and the cardiac region, with external electric and magnetic fields and frequencies below 100 kHz, are calculated separately using the equations (3) and (4) above.

4.1 Electrically Induced Current Densities

Calculations of the power absorbed in so-called block or cell models of the human body have been applied in determining the constants A for the cardiac region and the brain. Data originating from different authors and values of $\bar{A}$ are summarized by Bernhardt (1983).

The constant $\bar{A}$--and thus the current density--in elongate spheroids or in the head of block models is 10 to 20 times higher than the current density in the simple spherical model.

Apart from data from studies on the absorption in the high-frequency range, and beside the employment of the extrapolation method within the quasi-static range, A was determined also by calculating the current densities for the head and the thorax on the basis of the field strength measured on the body surface at 50/60 Hz (Kaune et al., 1980; Schneider et al., 1974). The $\bar{A}$-values, determined by entirely different methods, coincide; the factor of variation is as low as 2. As the problem here is only the determination of the magnitude of the body current densities, the same value, $\bar{A} = 3 \cdot 10^{-9}$ $S \cdot Hz^{-1} \cdot m^{-1}$, was applied in relation to the cardiac region and the head.

Figure 2 shows the values of the electric current density, applied to the cardiac region and to the head, as a function of frequency and the external electric field strength. The curves B, D, and A have been transferred from Figure 1, using equation (3) above, to Figure 2. The ordinate is plotted up to the value that is generally deemed the value of ionization of the air (roughly $3 \cdot 10^6$ Vm^{-1}).

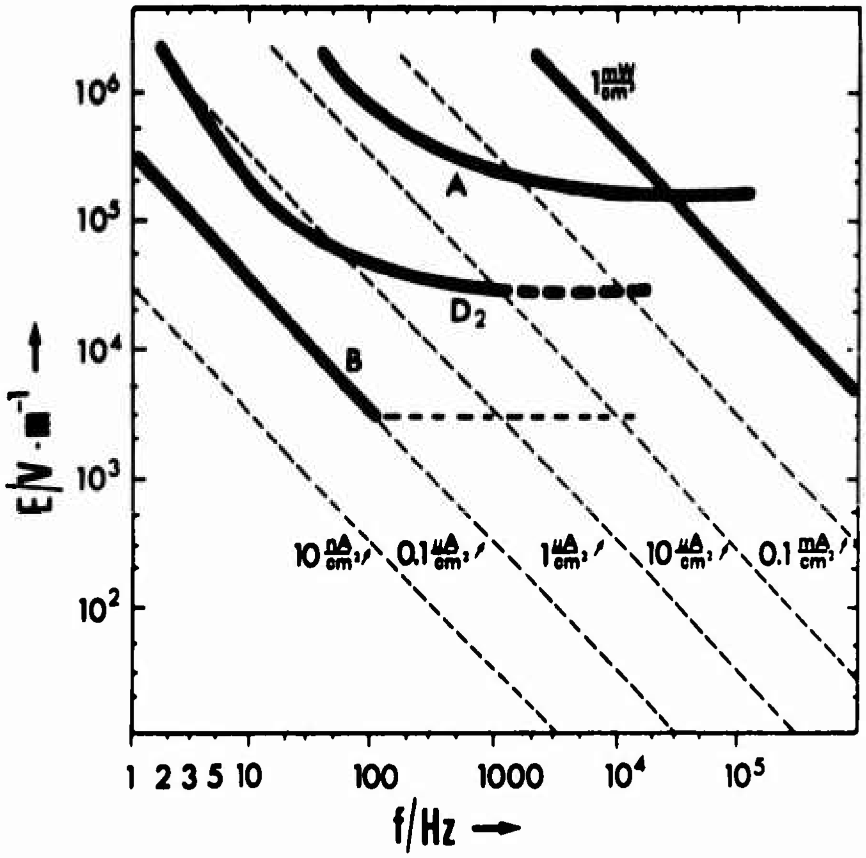

Figure 2. Electric field strength in man's environment, which induces approximately the indicated current density in the head and in the cardiac region (longitudinal axis of man parallel to orientation of the field; the numerical values given for the field strength apply to the undisturbed field).
Curve A: threshold value curve for stimulating effect
Curve B: limit curve of the safe range
Curve D: limit value curves with a sufficiently wide safety margin from the curve plotting the hazardous values

4.2 Magnetically Induced Current Densities

Different authors give different values for the low frequency conductivity of the myocardial tissue and the nerve tissue. In the model calculations set out here, differences in conductivity of the white and grey cerebral substance and the anisotropic nature of conductivity at frequencies below approximately 10 kHz are left out of consideration. A value of 0.2 $S \cdot m^{-1}$ has been used for the specific conductivity of the cerebral substance, while a value of 0.25 $S \cdot m^{-1}$ has been used for the myocardial tissue.

For R in equation (4), values of 7.5 cm for the head and 6 cm for the heart were substituted. As a result of the selection of σ, the products $\sigma \cdot R$ are equal for the heart and head; therefore, the current densities in the heart and in the brain may be presented by a single representation.

Figure 3 represents these current density values as a function of frequency and of the external magnetic field strength (magnetic induction). By application of equation (4), the curves B, D_2, A, and C_2 have been transferred from Figure 1 into this diagram. The values given for the current densities are applicable only to the peripheral regions of the heart or the head, e.g., in relation to the cerebral cortex, following the definition of equation (4). For zones closer to the center of the heart or the head, high values for the magnetic inductions are necessary to induce the same current densities.

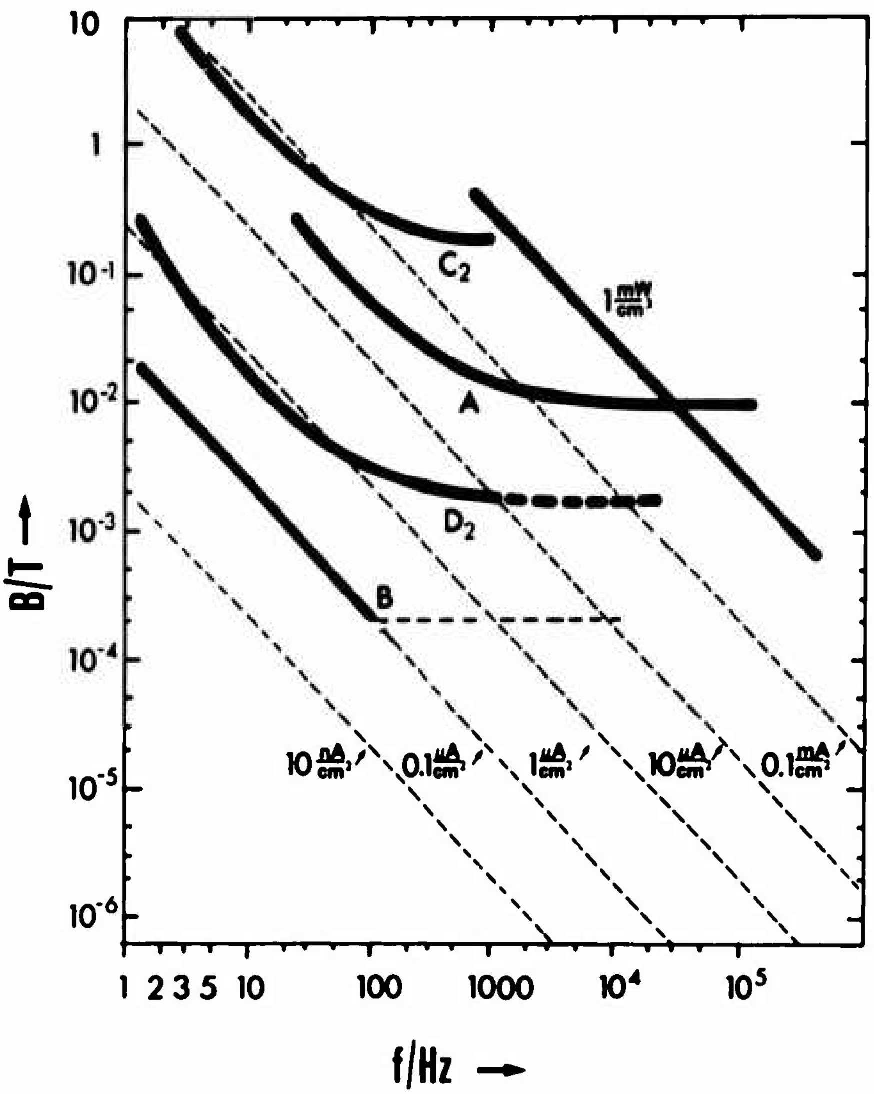

Figure 3. Magnetic induction in man's environment with sinusoidal variations of the field in relation to peripheral regions of the head and the heart, which induce the indicated current densities.
Curve A: threshold value curve for stimulating effects
Curve B: limit curve of the safe range
Curve C_2: diastole stimulation threshold
Curve D_2: limit value curves with a sufficiently wide safety margin from the curve plotting the hazardous values

5.0 CONCLUSIONS

The field strength/frequency diagrams initially permit a rapid orientation about the respective mean electric current densities that will have to be expected in the human head or heart, with predetermined external electric or magnetic field strengths as a function of frequency. The diagrams can be likewise applied to the exposure to fields in the power engineering range and to other frequencies. When the ordinate is used to plot the magnetic induction, the ordinate origin must be shifted upward or downward, in accordance with equation (4), for other radii or other conductivity characteristics.

The explanations given in section 3 on the relevance of curves B, D_2, and A, as well as on the safety factor, are equally valid here by way of analogy. Figure 2 shows that the stimulation threshold curve A can practically not be reached in case of exposure to external electric fields, as the required values of the electric field intensities are excessively high. Conditions are different, however, with magnetic fields. Industrial metal smelting and processing requires magnetic induction at levels far above the curve A. According to some measured data, the values required for stimulation of neurons are not reached, however, at working places. With values of the electric or magnetic field strength below curve B, an influence on neurons is not expected. In the event that biological effects should be noted with such field intensities, these effects must be based on action mechanisms other than those so far described. This is an important conclusion.

The statements given here are confirmed for the power engineering range of 50-Hz electric fields in so far as extensive laboratory and epidemiologic experiments and studies, so far carried through with both animals and test subjects with electric field intensities up to roughly 20 kV/m and with magnetic induction values of 0.3 mT, did not reveal any indication of effects involving a health hazard or affection (Bridges et al., 1981; Schaefer, 1983; Suess, 1981; UNEP, 1984).

When the limit value curve D_2 is used to evaluate human exposure to external electric and magnetic fields or as a basis of discussions on the definition and determination of personnel health limits, attention must be drawn again to the fact that Figures 2 and 3 are suited only to give an idea of the magnitude of the current density in the body. Mean values were taken as the basis to determine the distribution of the electric field in the heart and head; the exact current paths are not known. Local increases of the internal field intensity cannot be precluded. The extent of locally excessive field intensities needs further elucidation by continued study. Safety factors can be defined more precisely only by further studies. Long-term studies with animal experiments and epidemiologic examinations of personnel are particularly important methods.

One second (1 heart period) should be taken as a base for the exposure time for which the field strengths should be averaged. For shorter exposure times, higher values of field strength may be accepted. For exposure of the extremities to magnetic fields, special considerations are necessary, leading certainly to higher limiting values for the field strength.

The model described here, however, does not furnish any statement on the extent to which other factors and secondary effects must be considered in arriving at limit values. Examples are surface effects or currents flowing in

the body when metal objects are touched in which potentials are induced (burns and micro shocks; Gandhi et al., 1982); also the influence of fields on life-saving installations, pacemakers, etc. The evaluation of field strength levels that lead to perceptible but harmless effects may be different for the general population and for occupational exposure. It may be possible to eliminate perceptible effects for workers by suitable technical measures or to inform them of the secondary effects.

Levels of exposure of the general populations should be limited to values low enough to avoid perceptible effects, even if harmless--at least for their dwellings where a continuous exposure of persons cannot be excluded.

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